Numerical Modeling of Drying Residual RP-1 in Rocket Engines

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Introduction

When a Rocket Engine shuts down under a fuel rich environment, a significant amount of unburned RP-1 is trapped in the engine. It is necessary to clean the residual RP-1 prior to subsequent firing to avoid any explosion due to detonation. The conventional method is to dry RP-1 with inert gas such as Nitrogen or Helium. It is difficult to estimate the drying time unless the engine is adequately equipped with instruments to measure the trace of RP-1 during the drying process. Such instrumentation in flight hardware is often impractical and costly. On the other hand numerical modeling of the drying process can provide a good insight for a satisfactory operation of the process. A numerical model can provide answer to questions such as a) how long it takes to dry, b) which fluid is a better dryer for RP-1, c) how to reduce drying time etc.

The purpose of the present paper is to describe a numerical model of drying RP-1 trapped in a cavity with flowing nitrogen or helium. The numerical model assumes one-dimensional flow of drying fluid in contact with liquid pool of RP-1 (Figure –1). An evaporative mass transfer takes place across the contact surface.

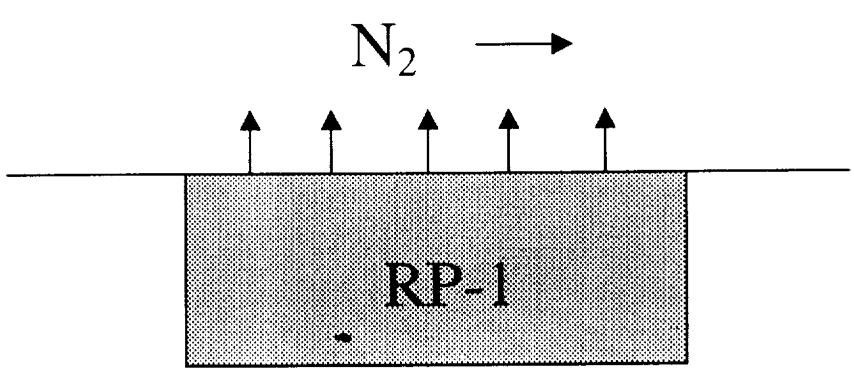

Figure –1 Drying of liquid RP-1 by gaseous Nitrogen

The considered problem was to find the rate of mass transfer of RP-1 into nitrogen stream for a given pressure, temperature and flowrate assuming no heat transfer between RP-1 and nitrogen. It is also assumed that mass transfer between liquid and gas occurs through a thin film separating two streams. This film contains saturated vapor at interface temperature, which is assumed to be at liquid temperature.

Governing Equations

The equations governing the mass transfer of liquid to a gaseous stream can be expressed as[1] :

Mass Transfer Rate, W_A (lb-mol/sec)

$$W_A = k_{xm} A \frac{x_{A0} - x_{A\infty}}{1 - x_{A0}} \tag{1}$$

Where x_{A0} is the mole fraction of vapor of the saturated film near the liquid surface and $x_{A\infty}$ is the mole fraction of vapor in the gaseous stream. A is the surface area and k_{xm} is mass transfer coefficient given by:

Mass Transfer Coefficient, k_{xm} (lb-mol/ft^2-sec)

$$\frac{k_{xm} L}{\rho_{mol} D_{AB}} = 2.0 + 0.60 \left(\frac{\rho_f v_\infty L}{\mu_f} \right)^{0.5} \left(\frac{\mu_f}{\rho_f D_{AB}} \right)^{0.33} \tag{2}$$

L is a characteristic length scale, ρ_f and μ_f are density and viscosity of vapor at film temperature. ρ_{mol} is the molar density, v_∞ is the free stream velocity of gas near the liquid surface. The diffusivity between liquid and gas, D_{AB} is given by:

Mass Diffusivity, D_{AB} (ft^2/sec)

$$\frac{p D_{AB}}{(p_{cA} p_{cB})^{1/3} (T_{cA} T_{cB})^{5/12} \left[\frac{1}{M_A} + \frac{1}{M_B} \right]^{0.5}} = a \left(\frac{T}{\sqrt{T_{cA} T_{cB}}} \right)^b \tag{3}$$

The subscript A and B refer to liquid and gas respectively. The subscript c refers to critical point and p and T are pressure and temperature respectively.

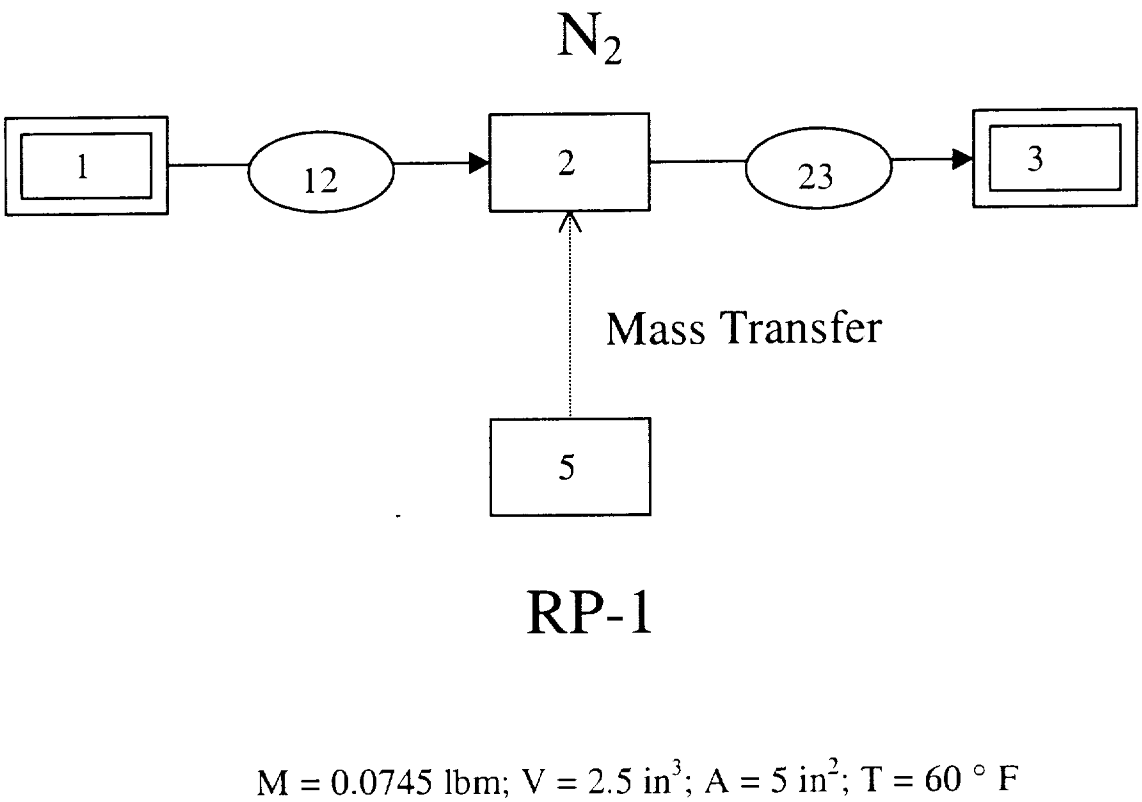

Figure 2 – GFSSP Model of mass transfer

GFSSP Model

A simple transient GFSSP (Generalized Fluid System Simulation Program[2]) model was constructed to estimate the evaporative mass transfer rate of RP-1 using nitrogen and helium as drying fluid. The model is shown in Figure 2. Figure shows that nitrogen is flowing through a duct and is in contact with RP-1 stored in a cavity. Node 1 and 3 are boundary nodes where pressure and temperature are specified. Node 2 and 5 are internal nodes where all scalar properties such as pressure, temperature and concentrations are calculated. Node 5 contains RP-1 of known initial mass, volume and temperature.

The mass transfer model described in equations 1 to 3 was implemented in User Subroutine of GFSSP. User Subroutine is an effective way of incorporating new physical model in the code. The GFSSP process flow diagram is shown in Figure 3. The code consists of three major modules: 1) Preprocessor, 2) Solver and Property Program and 3) User Subroutines. User creates the input data file with the help of the Preprocessor. GFSSP has two preprocessors: command line and visual. Solver and property program generates and solves all pertinent equations with the help of fluid property routines. User subroutines are set of blank subroutines called from solver module. This allows the user an opportunity to add or modify the governing equations according to their need. The developed user subroutine is then compiled and linked with solver module to create a customized executable.

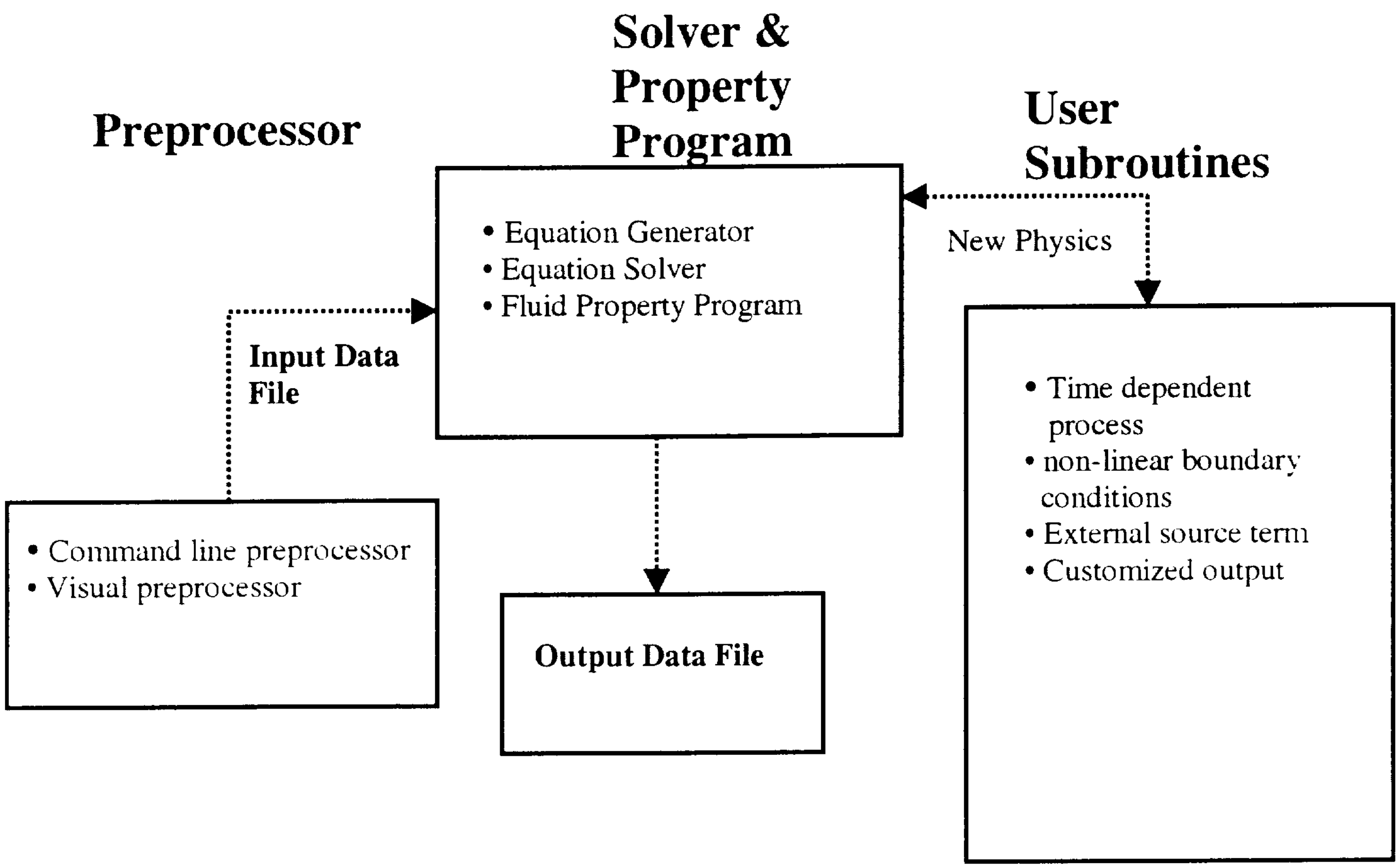

Figure 3. GFSSP Process Flow Diagram

Results

Several cases were run to study the effect of various parameters on drying time. The results of the parametric were shown in Table 1. Results indicate that a) Nitrogen is a better dryer of RP-1 than helium, b) Drying rate significantly increases at higher RP-1 temperature and c) Lower pressure and higher flowrate increases drying process.

References

1. "Transport Phenomenon" Bird, R. B., Stewart, W. E. and Lightfoot, E. N., John Wiley & Sons, 1960.
2. "Generalized Fluid System Simulation Program (GFSSP) Version 3.0" Alok Majumdar, Sverdrup Technology Report No. MG-99-290, November 1999.

Table 1. Results of Parametric Study

Case No.	Drying Fluid	P_{in} (psia)	P_{out} (psia)	T_{fluid} (°F)	T_{RP-1} (°F)	$\dot{m}_{fluid}$ (lbm/sec)	ΔX (x 10^3)	k_{xm} (x 10^4)	Drying Time (Hour)
1	N_2	**25**	**20**	**100**	**60**	**0.117**	**8.59**	**1.27**	**3.146**
2	N_2	**25**	**24**	**100**	**60**	**0.0489**	**7.93**	**0.85**	**5.001**
3	N_2	**25**	**20**	**100**	**90**	**0.117**	**13.59**	**1.27**	**1.922**
4	N_2	**25**	**20**	**75**	**90**	**0.120**	**13.59**	**1.26**	**1.935**
5	N_2	**55**	**50**	**100**	**90**	**0.183**	**5.86**	**1.63**	**3.523**
6	**He**	**25**	**20**	**100**	**60**	**0.039**	**8.6**	**0.196**	**20.002**
7	**He**	**25**	**1**	**100**	**60**	**0.833**	**12.4**	**0.238**	**11.67**